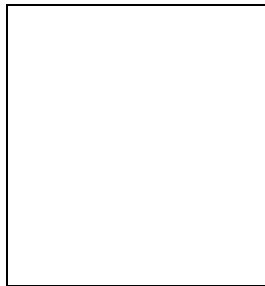# XIth International Conference on
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Medium-Modified Jet Shapes in Heavy-Ion Collisions

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Jet quenching has been established as one of the main tools to study the properties of the medium produced in heavy ion collisions. Most of the experimental effort has been, up to now, on the measurements of inclusive particle suppression. This observable suffers, however, of limitations due to different trigger-bias effects. The study of jets (or particle correlations) in a medium is the most promising way out for a better characterization of the medium properties. I will present how these more differential measurements can be used to study not only the density of the medium (the traditional parameter fixed by jet quenching measurements) but also more dynamical quantities as flow fields.

One of the more striking observations at RHIC so far is the strong suppression of the yields of particles produced at high transverse momentum in central nucleus-nucleus collisions[1]. The most widely accepted interpretation of this phenomenon is in terms of energy loss due to medium-induced gluon radiation[2]. The peculiar angular structure of this radiation, affected by formation time effects through LPM suppression, predicts a broadening of the jet-like signals associated to the high-p_t particles when compared with the corresponding ones in proton-proton collisions[3,4].

Inclusive particles. The evolution of a high-p_t parton shower is affected by the medium created in heavy ion collisions. At the leading particle level, the additional energy loss translates into a suppression of the high-p_t yields due to the steeply falling perturbative spectrum. The only free parameter describing the medium-induced gluon radiation is the transport coefficient $\hat{q}$ with the meaning of the transverse momentum transferred to the emitted gluon per mean free
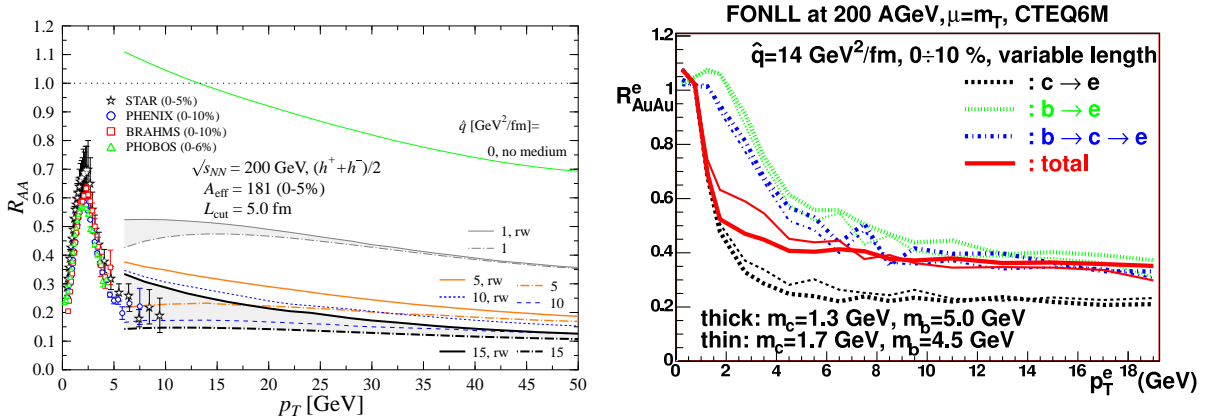
Figure 1: Left: nuclear modification factor R_{AA} for charged particles in central AuAu collisions at $\sqrt{s} = 200$ GeV compared with theoretical curves [6] for different values of $\hat{q}$. Right: Prediction [12] for the suppression of electrons coming from the decay of charm quarks in central AuAu collisions at $\sqrt{s} = 200$ GeV.

path. This energy loss is normally included [5] as a medium-modification of the fragmentation functions, through a convolution of the vacuum fragmentation function and the probability of an additional medium-induced energy loss $P(\epsilon, \hat{q}, L)$. The main goal in this type of analysis is to obtain the best value of the transport coefficient which fits the experimental data. All the medium properties accessible by this probe are encoded into this single variable. In Fig. 1 we plot the experimental data on light-meson suppression observed at RHIC together with the model calculations using different values of $\hat{q}$. The data is well reproduced for $\hat{q} = 5...15$ GeV^2/fm. Two comments are in order here. On the one hand the large uncertainty in the determination of this value is an intrinsic limitation of inclusive particle suppression as a measurement when the studied medium is very dense. The origin is a trigger bias effect that selects only those particles produced close to the surface due to the steeply falling spectrum of perturbatively produced partons[6,7]. On the other hand, this value is more than five times larger than estimates based on perturbative coupling of the traversing particles with the medium[8,6]. This has been interpreted as a signal of strong non-perturbative effects on the medium [6] or the coupling of the jet to dynamical properties of the medium as a flow field [13]. Both explanations open new possibilities for the study of high-p_t particles as probes to characterize the medium.

One possibility for further constrain the value of $\hat{q}$ is by changing the identity of the parent parton. In general color and mass factors imply a larger energy loss for gluons than for quarks and also larger for light than for heavy quarks [9]. The use of this property has been explicitly worked-out in [10] for both RHIC and the LHC. At present, heavy meson identification has not been possible at RHIC and the only information comes from the weak decays into electrons. In Fig. 1 our prediction for the electrons coming from the decays of D and B mesons is presented using the same value of $\hat{q}$ as obtained in the fit to the light mesons. Preliminary data[11] shows a strong suppression, compatible with a dominant contribution of the charm quark to the observed electrons spectrum. More work to understand the relative normalization of c and b production at RHIC energies is needed for a better understanding of the dynamical origin of this suppression.

Medium-modification of the jet shapes. The structure of the jets is expected to be strongly modified when developed in a medium. The larger emission angle of the medium-induced spectrum translates into a broadening of the jet shapes. A main issue in jet reconstruction (even in more elementary collisions) is the energy calibration. The amount of energy deposited into a jet cone of radius $R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$ is affected by two opposite effects, namely the out-of-cone fluctuations (which increase with the cone radius) and the background fluctuations (which decrease
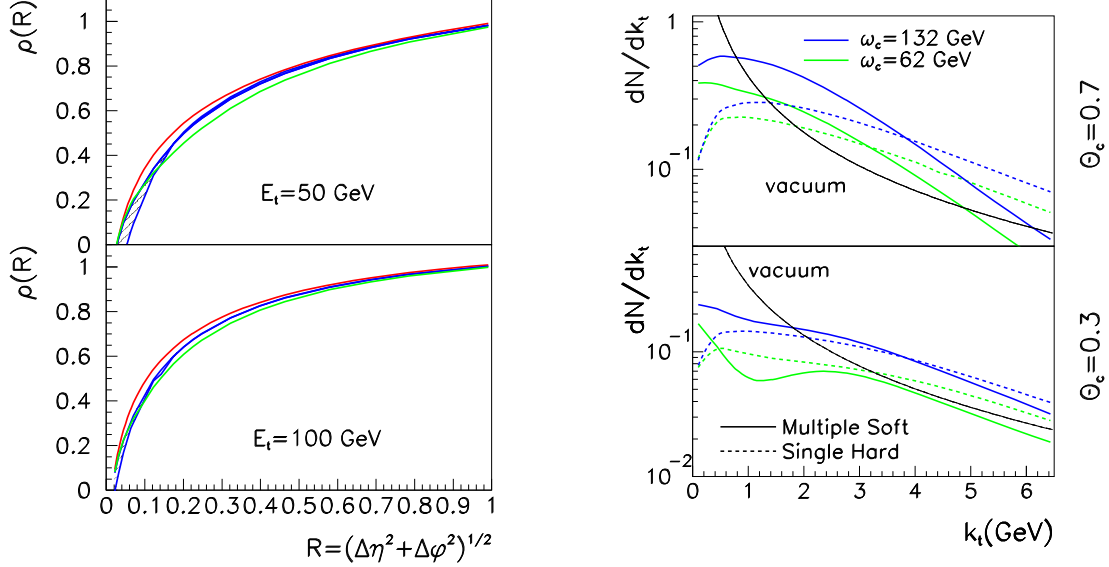
Figure 2: Left: Fraction of the jet energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ for a 50 GeV and 100 GeV quark jet fragmenting in the vacuum (red curves) and a hot medium. Right: Comparison of the vacuum and medium-induced part of the gluon multiplicity distributions inside a cone jet of size $R = \Theta_c$. Figures taken from [4].

with the cone radius). Dealing with the high-multiplicity background is the main difficulty in jet studies in heavy ion collisions. From a theoretical point of view, it is then, essential to identify jet observables in which the medium modification is not largely affected by the background.

In [4] the first study of this type of observables was performed. In particular we found a small broadening in the energy distributions inside a jet when computing the fraction $\rho(R)$ of the total jet energy deposited within a subcone of radius R. Physically, the gluons emitted at larger angles are softer and unable to redistribute a sizable amount of energy. As a consequence, the additional out-of-cone fluctuations are not enhanced dramatically. This general result is independent on imposing small-p_t cuts to the observed associated radiation, see Fig. 2 If the jet energy distribution is not modified by medium-effects the different structure of the radiation should manifest in the multiplicity distributions. In Fig. 2 we plot the additional number of medium-induced gluons as a function of their transverse momentum with respect to the jet axis for different values of the cone-radius $R = \Theta_c$. By imposing different cuts to the energy spectrum the sensitivity of this observable to background subtraction is shown to be small. It is worth noting that even though the present calculations lack of several physical mechanisms as hadronization etc, the main conclusions are independent on the actual realization of the model and depend solely on the general properties of the medium-induced gluon radiation; in particular the non-divergency of the spectrum in the infrared and collinear limits. These properties are given by formation time effects and kinematics.

At RHIC, a series of measurements on high-p_t particle correlations[11] point to the interesting possibility that the parton shower is strongly modified by dynamical medium properties as flow. From a theoretical point of view, the fundamental quantity describing a medium is the energy-momentum tensor $T^{\mu\nu} = (\epsilon+p)u^\mu u^\nu - p g^{\mu\nu}$ and this must, hence, be the object which determines $\hat{q}$. In a static medium we should recover the proportionality $\hat{q} = c\,\epsilon^{3/4}$[8], with ϵ the energy density. In the case of a transverse flow, the simplest extrapolation gives $\hat{q} = c'\,(T^{n_\perp n_\perp})^{3/4}$, where now $T^{n_\perp n_\perp}$ is given both by a non-flow symmetric component (density) and a antisymmetric flow field. One general conclusion is then that a flow field appears as an additional source of medium-induced gluon radiation, which mimics the effect of a static medium with larger density (see Fig. 3). Moreover, the most clear signature in the case the flow field is strong enough, is the distortion
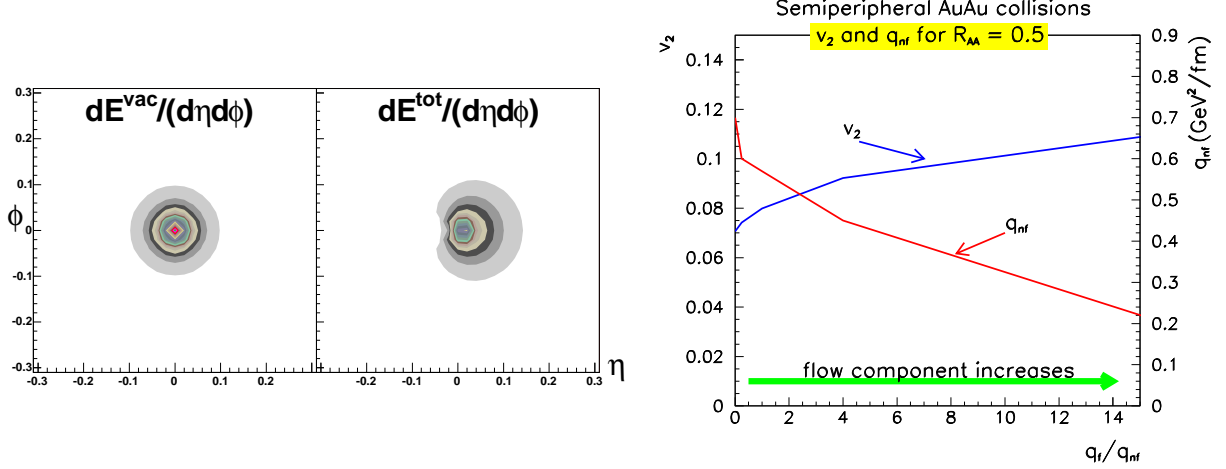
Figure 3: Left: Jet energy distributions in the $\eta \times \phi$ plane for a 100 GeV jet for a non-flowing (left panel) and flowing (right panel) medium. Right: Dependence of v_2 and non-flow component for the same $R_{AA} = 0.5$ in semiperipheral AuAu collisions.

of the jet shapes in the direction of the local flow field. Indeed, the associated radiation in the presence of a flow is no longer azimuth-symmetric as seen in Fig. 3. This opens new possibilities for studying dynamical properties of the produced medium by jet measurements.

References

1. K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88** (2002) 022301; C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **89** (2002) 202301; B. B. Back *et al.* [PHOBOS Collaboration], Phys. Lett. B **578** (2004) 297; I. Arsene *et al.* [BRAHMS Collaboration], Phys. Rev. Lett. **91** (2003) 072305.

2. For recent reviews see: R. Baier, D. Schiff and B. G. Zakharov, Ann. Rev. Nucl. Part. Sci. **50**, 37 (2000); M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077; A. Kovner and U. A. Wiedemann, arXiv:hep-ph/0304151; C. A. Salgado, Mod. Phys. Lett. A **19** (2004) 271; P. Jacobs and X. N. Wang, Prog. Part. Nucl. Phys. **54** (2005) 443

3. R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B **484** (1997) 265 [arXiv:hep-ph/9608322].

4. C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **93**, 042301 (2004)

5. X. N. Wang, Z. Huang and I. Sarcevic, Phys. Rev. Lett. **77** (1996) 231; M. Gyulassy, P. Levai and I. Vitev, Phys. Lett. B **538**, 282 (2002); C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **89**, 092303 (2002); Phys. Rev. D **68**, 014008 (2003).

6. K. J. Eskola, H. Honkanen, C. A. Salgado and U. A. Wiedemann, Nucl. Phys. A **747**, 511 (2005) [arXiv:hep-ph/0406319].

7. B. Muller, Phys. Rev. C **67** (2003) 061901 [arXiv:nucl-th/0208038]; A. Dainese, C. Loizides and G. Paic, Eur. Phys. J. C **38**, 461 (2005) [arXiv:hep-ph/0406201].

8. R. Baier, Nucl. Phys. A **715** (2003) 209

9. Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B **519** (2001) 199; N. Armesto, C.A. Salgado and U.A. Wiedemann, Phys. Rev. D **69** (2004) 114003; B. W. Zhang, E. Wang and X. N. Wang, Phys. Rev. Lett. **93** (2004) 072301; M. Djordjevic and M. Gyulassy, Nucl. Phys. A **733** (2004) 265.

10. N. Armesto, A. Dainese, C. A. Salgado and U. A. Wiedemann, Phys. Rev. D **71**, 054027 (2005) [arXiv:hep-ph/0501225].

11. Proceedings of Quark Matter 2005 Conference, to be published in Nucl. Phys. A.

12. N. Armesto, A. Dainese, M. Cacciari, C.A. Salgado and U.A. Wiedemann, in preparation.

13. N. Armesto, C. A. Salgado and U. A. Wiedemann, Phys. Rev. Lett. **93**, 242301 (2004) [arXiv:hep-ph/0405301]; arXiv:hep-ph/0411341.